

# Chiral Partners and their Electromagnetic Radiation

## (Ingredients for a systematic in-medium calculation)

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### Abstract

It is argued that the chiral partners of the lowest-lying hadrons are hadronic molecules and not three-quark or quark-antiquark states, respectively. As an example the case of  $a_1$  as the chiral partner of the  $\rho$  is discussed. Deconfinement — or as a precursor large in-medium widths for hadronic states — is proposed as a natural way to accommodate for the fact that at chiral restoration the respective in-medium spectra of chiral partners must become degenerate. Ingredients for a systematic and self-consistent in-medium calculation are presented with special emphasis on vector-meson dominance which emerges from a recently proposed systematic counting scheme for the mesonic sector including pseudoscalar and vector mesons as active degrees of freedom.

## 1 Chiral partners

Chiral symmetry breaking and its restoration in a strongly interacting medium is one of the key issues of in-medium hadron physics, at least for the states made out of light ( $u$ ,  $d$ ,  $s$ ) quarks (see e.g. the talk of T. Hatsuda in the present proceedings volume). One of the clearest signs that chiral symmetry is indeed spontaneously broken comes from a comparison of the spectra of quark currents related by a chiral transformation, namely the vector-isovector current  $\vec{j}_V^\mu = \bar{q}\vec{\tau}\gamma^\mu q$  and the axial-vector-isovector current  $\vec{j}_A^\mu = \bar{q}\vec{\tau}\gamma_5\gamma^\mu q$ .<sup>1</sup> If chiral symmetry was realized in the same way as, say, isospin symmetry, then the spectra of the respective current-current correlators would be (approximately) the same. The experimental results for these spectra are shown in Fig. 1. Obviously the spectra are not identical, not even approximately. In particular, the vector spectrum (Fig. 1, left) shows a peak below 1 GeV, the  $\rho$  meson, whereas the axial-vector spectrum (Fig. 1, right) does not show any structure below 1 GeV, but instead a broad bump at around 1.2 GeV, the  $a_1$  meson. Since the vector and the axial-vector current are related by a chiral transformation one can call these quark currents chiral partners at the fundamental level. It is suggestive to call  $\rho$  and  $a_1$  chiral partners at the hadronic level since they couple to the respective quark currents as seen in Fig. 1. Obviously, due to chiral symmetry breaking the masses of  $\rho$  and  $a_1$  are not the same. In the following we shall show strong indications that chiral partners are even different in nature. To which extent the phrase “chiral partners” is pure semantics or contains physics is discussed in more detail in [2].

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<sup>1</sup>Here  $\vec{\tau}$  denotes the isospin matrices. A generalization to flavor SU(3) is straightforward.

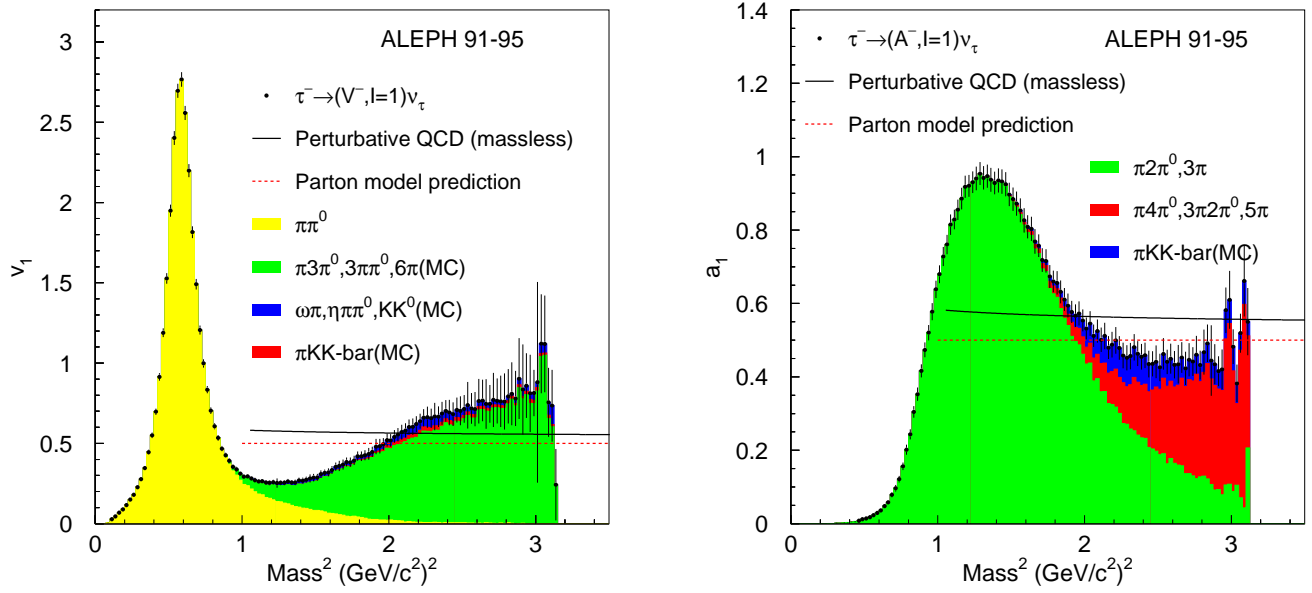


Figure 1: Spectral information of the vector (*left*) and axial-vector (*right*) current. Figs. taken from [1].

## 2 Nature of chiral partners

We start with the lowest-lying hadronic states (in flavor SU(3)), the nucleon octet, the pion nonet, the  $\Delta$  decuplet and the  $\rho$  nonet. In the following we assign to these states the label “LLH” (= lowest-lying hadrons). Without much doubt these states are dominantly quark-antiquark or three-quark states, respectively (concerning the  $\rho$  meson see e.g. [2]). On the other hand, the chiral partners of the LLH states can be understood as dynamically generated states, i.e. in a somewhat oversimplified language as hadronic “molecules”. For the  $N^*(1535)$ , the chiral partner of the nucleon, it has been demonstrated in [3] and many follow-up works that it emerges from the coupled-channel dynamics of  $\eta N$ ,  $K\Lambda$ , .... Many works have been devoted to the  $\sigma$  meson, the chiral partner of the pion. For example in [4] the  $\sigma$  emerges as a dynamically generated state in pion-pion scattering. In [5] it has been argued that the  $\Delta^*(1700)$ , the  $N^*(1520)$  and their respective flavor partners, which can be seen as the chiral partners of the  $\Delta$  decuplet, are hadronic coupled-channel “molecules”. Finally the  $a_1$  multiplet is generated dynamically in [6]. We note in passing that also the  $b_1$  multiplet can be viewed as the chiral partner of the  $\rho$  multiplet [7]. This apparent ambiguity is resolved in the sense that also the  $b_1$  multiplet is generated on equal footing in [6].

The works cited above essentially use the same framework for dynamical generation: One studies the scattering of an LLH state on Goldstone bosons for the channel of interest, i.e. the one with the quantum numbers of the chiral partner of the LLH state. The scattering matrix  $T$  is determined from the Bethe-Salpeter equation as shown on the left-hand side of Fig. 2. The input for the Bethe-Salpeter equation, the interaction kernel, is always of the same type: One considers the lowest order of the chiral interaction, the Weinberg-Tomozawa point interaction [8]. Consequently, due to chiral symmetry breaking, the strength of this interaction is fixed model independently  $\sim F_\pi^{-2}$ , where  $F_\pi$  denotes the pion-decay constant. The Bethe-Salpeter equation requires renormalization to obtain a well-defined meaning. As shown in [6, 9] the renormalization point for the loop appearing in the Bethe-Salpeter equation is actually fixed, e.g. by requiring approximate crossing symmetry for the scattering matrix  $T$  [5, 6]. Thus, there are no free parameters for the calculation of the scattering amplitude using the leading order chiral interaction as an input. Peaks in the scattering amplitude signal the appearance of

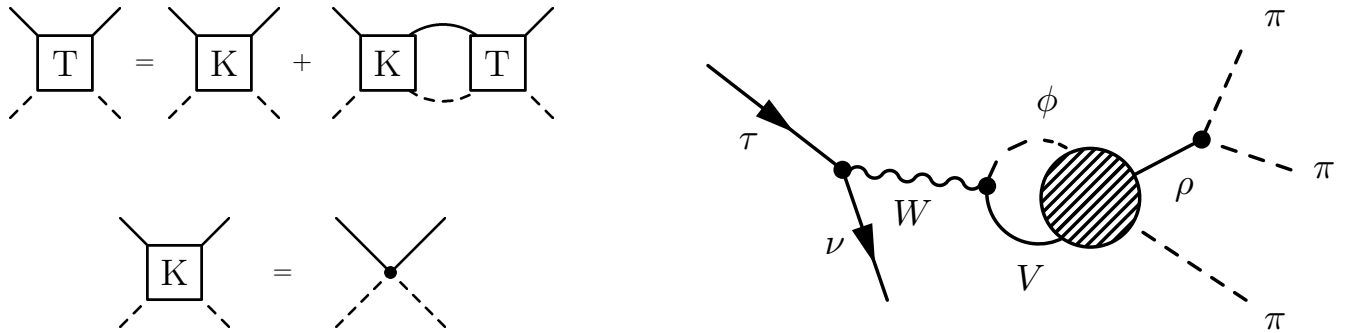


Figure 2: *Left, top:* Generic Bethe-Salpeter equation for the scattering of a Goldstone boson (dashed lines) on an LLH state (full lines). *Left, bottom:* In the framework described in the main text the kernel  $K$  of the Bethe-Salpeter equation is the chiral lowest-order interaction, the Weinberg-Tomozawa point interaction. *Right:* Description of the decay  $\tau \rightarrow \nu_\tau + 3\pi$  with the  $a_1$  as a final-state interaction effect. The blob denotes the S matrix for the scattering of pseudoscalar states  $\phi$  on vector states  $V$ . See main text for details.

dynamically generated resonances.

In the following we concentrate on one specific channel, namely on (the low-energy part of) the axial-vector spectrum shown in Fig. 1, right. Not shown is the fact that there is more differential information available, namely Dalitz plots for the three-pion hadronic final state. These Dalitz plots show that the three-pion final state is correlated to a  $\pi$ - $\rho$  state [11]. Above we have described the scenario where the chiral partners of the LLH states are dynamically generated. For the case at hand this implies that the two-body state of vector meson and Goldstone boson is subject to a strong final-state interaction which creates the  $a_1$  bump seen in Fig. 1, right. We shall study in the following how well this scenario works. The corresponding processes are depicted in Fig. 2: The right panel shows the whole process from which the experimental information is extracted, the decay  $\tau \rightarrow \nu + 3\pi$ . From the weak-interaction vertex the hadronic two-body state of vector meson and Goldstone boson emerges ( $\rho$ - $\pi$  and  $K^*$ - $K$ ). Its final-state interaction is obtained from the Bethe-Salpeter equation [6, 10] shown on the left-hand side of Fig. 2 and described above. There is one parameter not fixed by the general considerations: the renormalization point,  $\mu_2$ , of the entrance loop for the rescattering process, i.e. the loop explicitly displayed in Fig. 2, right. Essentially it renormalizes the  $W$ -to-hadrons vertex. We keep the renormalization point  $\mu_2$  as a free parameter and study in Fig. 3, left, how the results depend on it [11]. Also shown in this plot are the three-pion final-state data from [1]. Obviously, the variation of the only free parameter  $\mu_2$  changes height and width of the result, but not so much the peak position of the dynamically generated  $a_1$  state. In addition, one sees that a good agreement with the data (peak position, height and width) is obtained with only one free parameter [11]. This success supports the scenario of dynamical generation of the chiral partners of the LLH states.

### 3 What happens at chiral restoration?

Typically a spontaneous symmetry breaking is lifted at some temperature and/or density. (For example, for a Ferro magnet the spontaneous magnetization vanishes and rotational invariance is restored at the Curie temperature.) Consequently, the spectral information of the vector and the axial-vector current become identical at the point of chiral restoration. There are various scenarios conceivable how this degenerate in-medium spectrum might look like [12]. Here we briefly discuss only two. The degeneracy scenario: In vacuum the  $\rho$  meson is dominantly a single-particle state at the hadronic level (and not a pion-pion correlation [2]). If the  $\rho$  meson was still dominantly a single-particle state at the point of chiral restoration — i.e. if it still shows up as a prominent peak in the spectrum —, this would

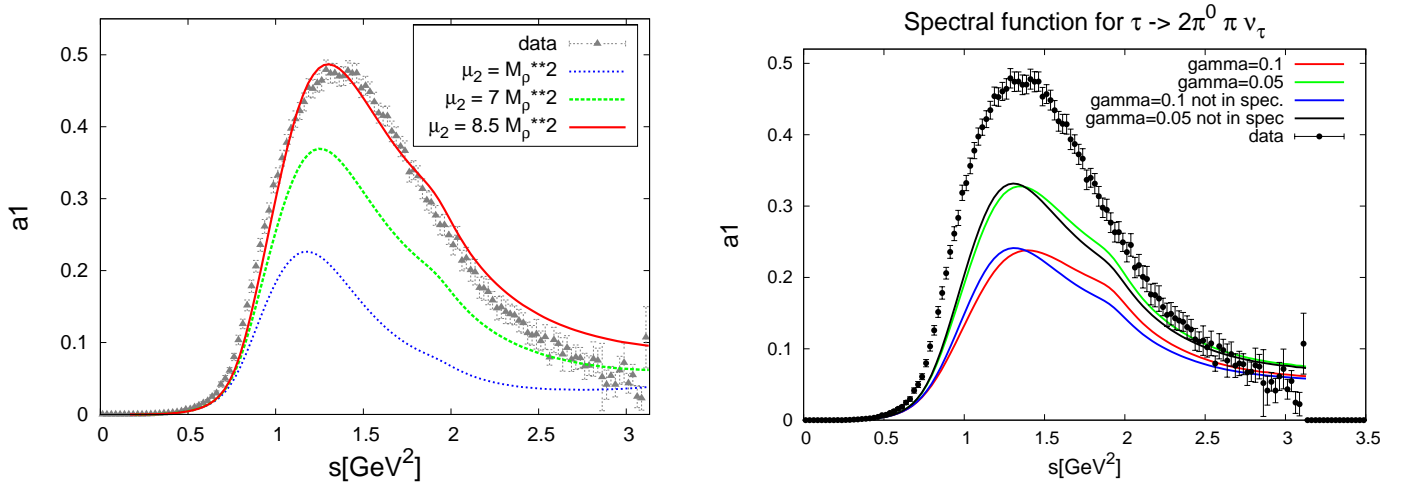


Figure 3: *Left:* Low-energy, i.e. 3-pion spectral information, of the axial-vector current in the scenario where the  $a_1$  is dynamically generated as compared to data. Figure taken from [11]. *Right:* Corresponding in-medium spectrum from a simple model. Figure taken from [2]. See main text for details.

require the existence of another single-particle state at the hadronic level with opposite parity, i.e. an axial-vector state. Since we have shown that the  $a_1$  meson is well described as a two-particle state, a  $\rho$ - $\pi$  correlation, there should be another, i.e. higher-lying axial-vector state which becomes degenerate with the  $\rho$  meson. We cannot exclude this possibility, but would regard it as rather unnatural that in vacuum such a state is so high in mass. Within our formalism we have not much to say about this scenario. The melting scenario: It might appear that the  $\rho$  meson dissolves already in hadronic matter. This should be understood as a precursor to deconfinement [13]. Then also the  $a_1$  meson should dissolve. In principle, this can be tested in our approach. In the following we present a very simple model: We increase the width of the  $\rho$  meson by a constant (by 50 or 100 MeV, respectively) and study what happens to the dynamically generated  $a_1$ . It must be stressed that this model should be regarded as a precursor to more serious calculations. In particular, an in-medium width of the  $\rho$  meson would not be independent of the momentum of the  $\rho$  meson relative to the medium [14]. In addition, one also expects a strong in-medium effect on the pion and not only on the  $\rho$  meson (see e.g. [14] and references therein). These aspects are not covered by the simple model studied here. The result is shown in Fig. 3, right. The upper/lower two curves correspond to an increase of the  $\rho$  meson width by 50/100 MeV. The difference between the respective two curves close to each other is not relevant for the present purpose.<sup>2</sup> Obviously, the  $a_1$  meson also melts, if the  $\rho$  meson melts. This does not prove that the melting scenario is the correct approach to chiral restoration, but at least we obtained a consistent picture. In a somewhat sloppy way, one might say that the problem of the missing partner of the  $\rho$  meson on the single-particle level is solved by deconfinement.

## 4 On vector-meson dominance

The in-medium calculation briefly discussed in the previous section should be regarded as a precursor to more serious considerations. Both for the understanding of the nature of resonances and for improved in-medium calculations, it clearly would be desirable to have a scheme at hand which goes beyond pure hadronic model building. Such a scheme should allow for systematic calculations, i.e. provide a power counting such that one has a serious reason to consider or disregard specific processes or diagrams. To operate in the energy region of resonances such a scheme should at least contain the LLH states, i.e. the

<sup>2</sup>For one curve all vector-meson propagators in the rescattering process are changed, for the other only (the last) one.

pion nonet, the  $\rho$  nonet, the nucleon octet, and the  $\Delta$  decuplet. For the meson sector such a scheme has been suggested recently in [15]. Some of its features are: Pseudoscalar and vector mesons are treated as soft. This allows for a systematic inclusion of decays of vector mesons. It yields clear statements about the validity of vector-meson dominance (VMD). Finally, an interesting aspect on the technical level is that vector mesons are represented by antisymmetric tensor fields. Clearly, also for one of the most interesting probes of relativistic heavy-ion physics, the dilepton production (cf. the corresponding contributions in the present proceedings) the issue of VMD is of central importance. A justification for the scheme proposed in [15] comes from large- $N_c$  considerations, where  $N_c$  denotes the number of colors [15]. We note in passing that an alternative justification emerges from the assumption of vector mesons as dormant Goldstone bosons [7]. Treating both vector and pseudoscalar states as soft essentially leads to the same counting rules. In addition, it strongly suggests the use of the antisymmetric tensor fields. We pick out two examples related to VMD for vacuum processes. According to the scheme presented in [15] both main decay channels of the  $\omega$  meson, the three-pion as well as the  $\pi^0$ - $\gamma$  decay, are governed in leading order by VMD. This is visualized in Fig. 4. Consequently, one can use e.g. the

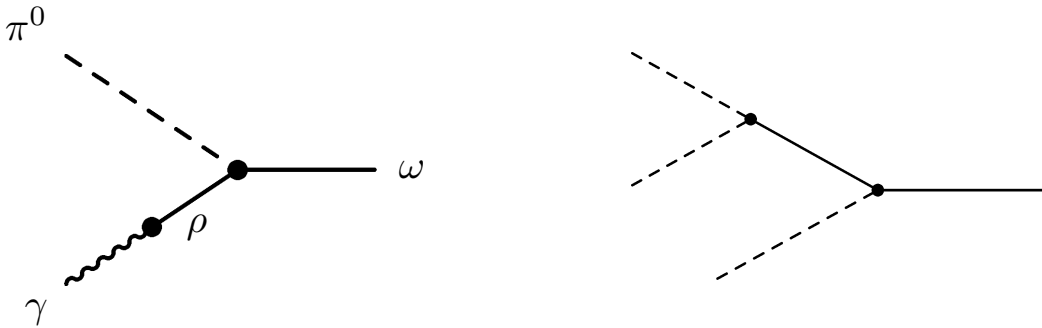


Figure 4: Vector-meson dominance for the main decay channels of the  $\omega$  meson.

decay  $\omega \rightarrow \pi^0 \gamma$  to fix the required coupling constant (the  $\omega$ - $\rho$ - $\pi$  coupling) and obtain a prediction for the three-pion decay [16]. One gets in that way  $\Gamma_{\omega \rightarrow 3\pi} = 7.3 \text{ MeV}$ , which is in excellent agreement with the experimental value  $\Gamma_{\omega \rightarrow 3\pi}^{\text{exp}} = (7.57 \pm 0.13) \text{ MeV}$ . On the other hand, the scheme of [15] does *not* yield VMD for every conceivable process. One counter example are the multipole moments of the vector mesons [15]. Another example, which we discuss now in some detail, concerns again the dynamically generated axial-vector states. Here VMD does not hold as can be seen diagrammatically in Fig. 5. The VMD process is depicted by diagram 5) of Fig. 5. It relates two decay processes to each other: the decay of the axial-vector state into its constituents (vector and pseudoscalar meson) and the decay into photon and pseudoscalar meson. However, also the other diagrams shown in Fig. 5 contribute sizably to the radiative decays of the axial-vector “molecules” [15]. In particular, the processes where the photon couples to the constituents of the “molecule” turn out to be important, the contributions of type 1) in Fig. 5. The finding that VMD does not work for the radiative decays of dynamically generated states is not restricted to the axial-vector mesons. It also applies e.g. to the baryon resonances which play an important role for the description of the in-medium dilepton production (see e.g. [14] and references therein). The absence of VMD does, of course, not imply that the interaction of dynamically generated states with real or virtual photons cannot be calculated. Quite on the contrary, the scheme of [15] (once extended to baryons) provides a systematic framework to determine these processes. The necessary input involves the electromagnetic moments of the constituents of the dynamically generated states, i.e. of the LLH states. While these moments are well determined for the nucleon, it is not so easy to get reliable estimates for the vector-meson and the  $\Delta$ -decuplet states. For example, the vector mesons in general have non-vanishing dipole and quadrupole moments. Here lattice QCD might help in the future. Otherwise one has to determine these couplings from fits to data.

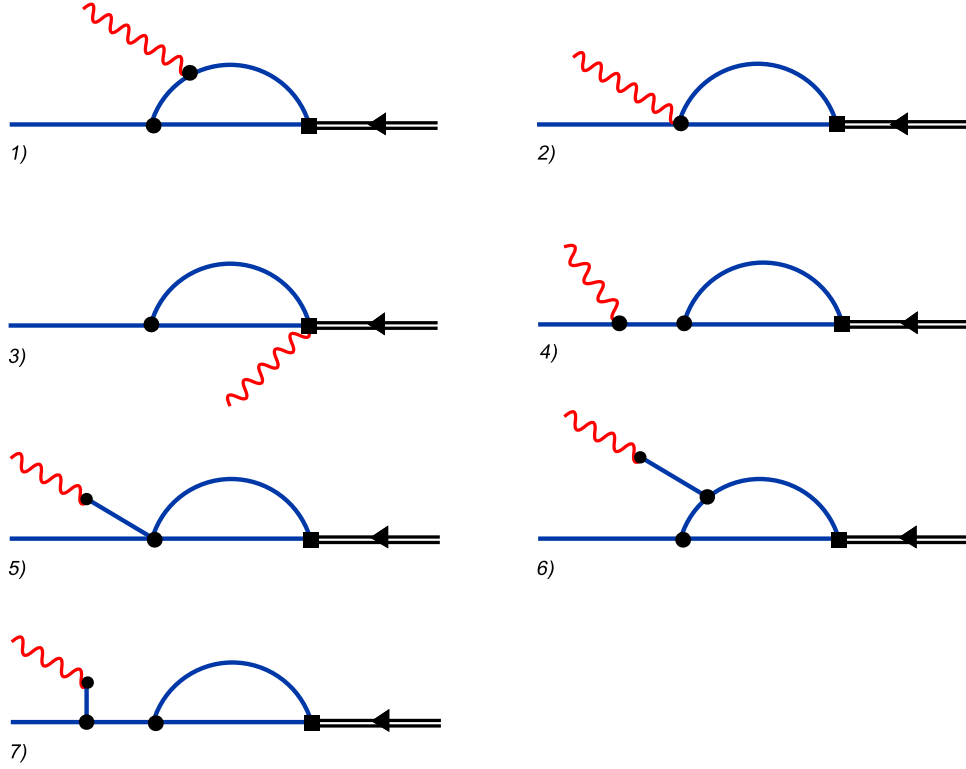


Figure 5: No vector-meson dominance for dynamically generated states. Double lines denote dynamically generated states, full lines their constituents, wavy lines photons. See main text for details. Figure taken from [15].

## 5 Towards self-consistent in-medium calculations

For relativistic heavy-ion physics concerning e.g. the production of particles like dileptons, hadronic in-medium calculations serve as an input to fireball-model or hydrodynamical calculations, but also yield in-medium cross sections relevant for transport approaches. Besides the description of existing data and predictions for upcoming experiments like e.g. CBM at FAIR (which largely operates in the hadronic regime), one would like to understand the relation between in-medium modifications and chiral symmetry breaking and restoration. To make further progress in that area on the theory side requires several ingredients. In the following we highlight two of them: First, a systematic framework instead of pure model building for the vacuum input and, second, a self-consistent in-medium scheme which allows to go beyond a low-density expansion to account for the mutual interactions between the constituents of a strongly interacting system. Concerning the elementary (vacuum) input one should incorporate the ideas of effective field theory to get from pure hadronic model building towards systematic approaches. The latter can assess quantitatively the intrinsic uncertainties and justify the neglect or incorporation of processes/diagrams. We have discussed the development of such a scheme in the previous sections. At the hadronic level the elementary relevant degrees of freedom are (at least) the lowest-lying hadron states, LLH states. In that scheme the chiral partners of the LLH states are not elementary at the hadronic level, but generated from coupled-channel dynamics. In that way, one already incorporates many resonances relevant for in-medium physics [14]. Of course, there remain some states which are not at all related to the LLH states by chiral transformations, in particular the negative-parity mesons and the positive-parity baryons. Whether these states can also be generated dynamically, as advocated by the hadrogenesis conjecture [5, 6, 15], remains to be seen [17]. It should be clear that this scheme offers a deep relation between in-medium physics and chiral symmetry breaking as discussed in Section 3. The in-medium changes of the dynamically generated chiral partners of the LLH states cannot be

decoupled from the aspect of chiral symmetry since their shear existence is caused by chiral dynamics. One connection to experiment are electromagnetic observables. On the elementary level (vacuum) they serve as a diagnostic probe for the intrinsic structure of the molecule-like states. In the context of relativistic heavy-ion physics dileptons allow to study the in-medium properties of hadrons. On the one hand, this concerns, of course, the vector mesons. Here vector-meson dominance (VMD) comes into play. As pointed out in Section 4, the systematic scheme developed in [15] provides clear predictions where VMD holds in leading order and where it does not. On the other hand, in a strongly interacting system the vector mesons in turn involve other resonances which then also become important for the dilepton production (see e.g. [14] and references therein). Finally we shall briefly comment on the required self-consistent in-medium framework. The simplest approach to in-medium physics is the linear-density approximation. It already provides a formidable task since in many cases the elementary input is not completely constrained by experiment. Here the systematic scheme discussed above comes into play. For a given hadron the linear-density approximation already yields in-medium changes of its properties which are due to the fact that this hadrons interacts with the constituents of the medium. However, also the other hadrons might change their properties as a response to the change of properties of the originally considered hadron (“changes induce changes”). This back reaction is not accounted for in a linear-density approximation. The mutual back reactions should be determined in a self-consistent framework. Recently it has been suggested in [18] how to overcome some obstacles of such schemes concerning intrinsic symmetries like chiral symmetry or current conservation. We note in passing that one key is the use of antisymmetric tensor fields to represent vector mesons. The systematic framework for the vacuum input discussed above was anyway designed in that manner. Hence, self-consistent in-medium calculations with a systematic vacuum input are required and possible [18, 19]. One task will be to check the validity of the melting scenario for chiral restoration as proposed in Section 3.

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